Photovoltaics and solar cell

Prerequisite/Recapitulations

- Semiconductor:
- Intrinsic and extrinsic Diode

Objectives

Solar Cell and its working
Efficiency of solar cell

Introduction

Solar cells and photo-detectors are devices that convert an optical input into current. A solar cell is an example of a photovoltaic device, i.e, a device that generates voltage when exposed to light. The photovoltaic effect was discovered by Alexander-Edmond Becquerel in 1839, in a junction formed between an electrode (platinum) and an electrolyte (silver chloride). The 1st photovoltaic device was built, using a Si pn junction, by Russell Ohl in 1939. The functioning of a solar cell is similar to the photodiode (photodetector). It is a photodiode that is unbiased and connected to a load (impedance).

There are three qualitative differences between a solar cell and photodetector

1. A photodiode works on a narrow range of wavelength while solar cells need to work over a broad spectral range (solar spectrum).
2. Solar cells are typically wide area devices to maximize exposure.
3. In photodiodes the metric is quantum efficiency, which defines the signal to noise ratio, while for solar cells, it is the power conversion efficiency, which is the power delivered per incident solar energy. Usually, solar cells and the external load they are connected to are designed to maximize the delivered power.

Introduction

Solar cells are typically illuminated with sunlight and are intended to convert the solar energy into electrical energy. The solar energy is in the form of electromagnetic radiation, more specifically "black-body" radiation. The sun's spectrum is consistent with that of a black body at a temperature of 5800 K. The radiation spectrum has a peak at 0.8 eV. A significant part of the spectrum is in the visible range of the spectrum (400 - 700 nm). The power density is approximately 100 mW/cm^2

Part of the solar spectrum actually makes it to the earth's surface. Scattering and absorption in the earth's atmosphere, and the incident angle affect the incident power density. Therefore, the available power density depends on the time of the day, the season and the latitude of a specific location.

Of the solar light, which does reach a solar cell, only photons with energy larger than the energy bandgap of the semiconductor generate electron-hole pairs. In addition, one finds that the voltage across the solar cell at the point where it delivers its maximum power is less than the bandgap energy in electron volt. The overall power-conversion efficiency of single-crystalline solar cells ranges from 10 to 30 % yielding 10 to 30 mW/cm^2.

Solar cell working principle

A simple solar cell is a pn junction diode. The schematic of the device is shown in this Figure . The n region is heavily doped and thin so that the light can penetrate through it easily. The p region is lightly doped so that most of the depletion region lies in the p side. The penetration depends on the wave-length and the absorption coefficient increases as the wavelength decreases. Electron hole pairs (EHPs) are mainly created in the depletion region and due to the built-in potential and electric field, electrons move to the n region and the holes to the p region. When an external load is applied, the excess electrons travel through the load to recombine with the excess holes. Electrons and holes are also generated with the p and n regions, as seen from figure.

The shorter wavelengths (higher absorption coefficient) are absorbed in the n region and the longer wavelengths are absorbed in the bulk of the p region. Some of the EHPs generated in these regions can also contribute to the current.

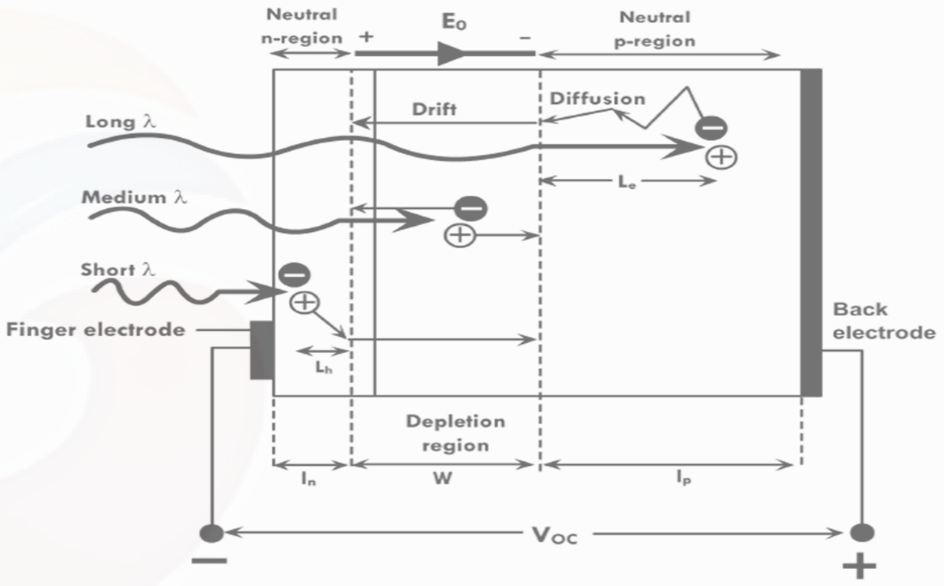


Figure : Principle of operation of a pn junction solar cell. Radiation is absorbed in the depletion region and produces electrons and holes. These are separated by the built-in potential. Depending on the wavelength and the thickness different parts of the device can absorb different regions of the solar spectrum. Adapted from Principles of Electronic Materials - S.O. Kasap

Photovoltaics

Solar cell working principle

Typically, these are EHPs that are generated within the minority carrier diffusion length, Le for electrons in the p side and Lh for holes in the n side. Carriers produced in this region can also diffuse into the depletion region and contribute to the current.

Thus, the total width of the region that contributes to the solar cell current is wd + Le + Lh, where wd is the depletion width. This is shown in this figure. The carriers are extracted by metal electrodes on either side. A finger electrode is used on the top to make the electrical contact, so that there is sufficient surface for the light to penetrate.

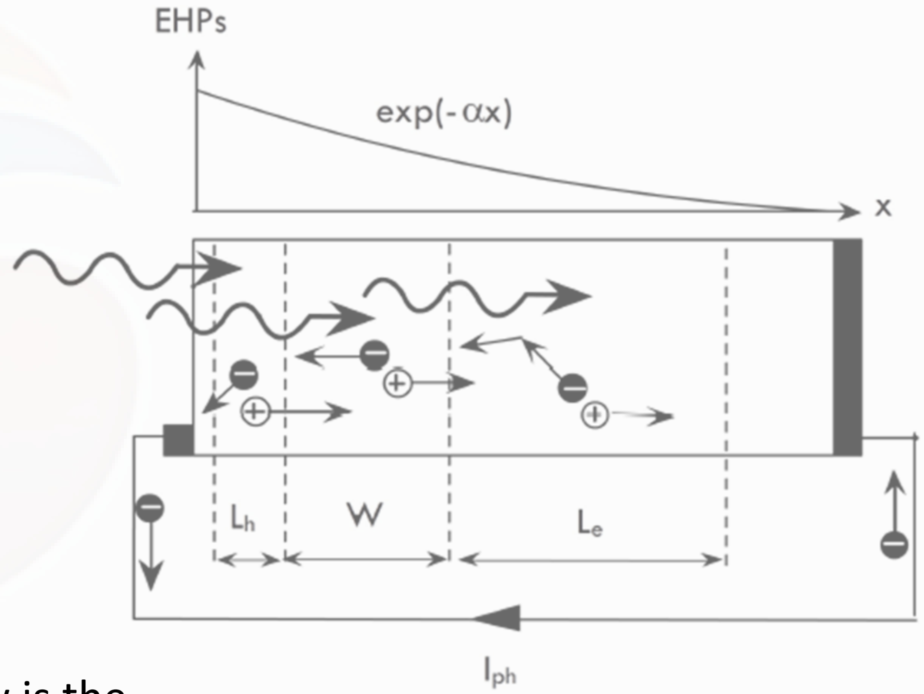


Figure : Photo generated carriers in a solar cell due to absorption of light. w is the width of the depletion region, while Lh and Le are minority carrier diffusion lengths in the n and p regions. The amount of absorption reduces with depth and hence the depletion region must be close to the surface to maximize absorption. This is achieved by having a thin n region. Adapted from Principles of Electronic Materials - S.O. Kasap

Solar cell working principle

The carriers are extracted by metal electrodes on either side. A finger electrode is used on the top to make the electrical contact, so that there is sufficient surface for the light to penetrate. The arrangement of the top electrode is shown in this figure.

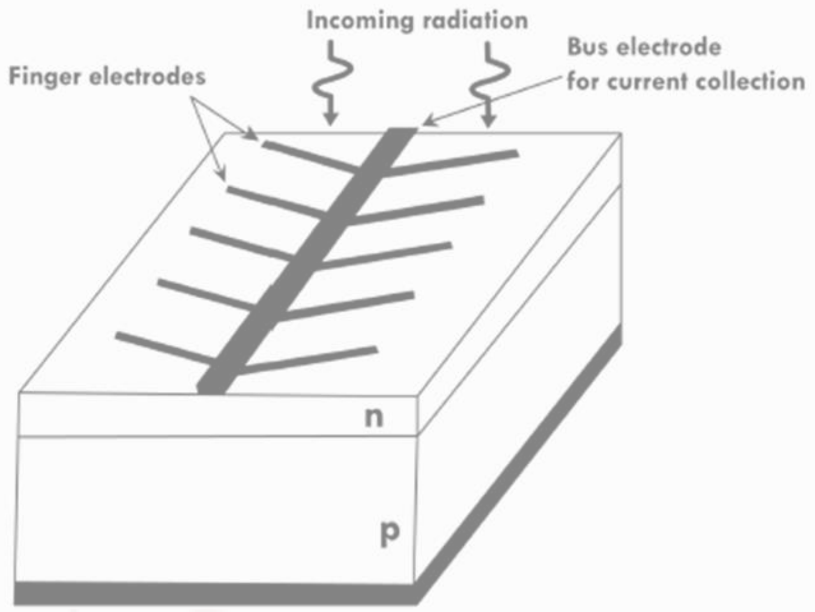


Figure : Finger electrodes on a pn junction solar cell. The design consists of a single bus electrode for carrying current and finger electrodes that are thin enough so that sufficient light can be absorbed by the solar cell. Adapted from Principles of Electronic Materials - S.O. Kasap

Solar cell working principle

Consider a solar cell made of Si. The band gap, Eg, is 1.1 eV so that wave-length above 1.1 μm is not absorbed since the energy is lower than the band gap. Thus any greater than 1.1 μm has negligible absorption. For much smaller than 1.1 μm the absorption coefficient is very high and the EHPs are generated near the surface and can get trapped near the surface defects. So there is an optimum range of wavelengths where EHPs can contribute to photocurrent, shown in this figure.

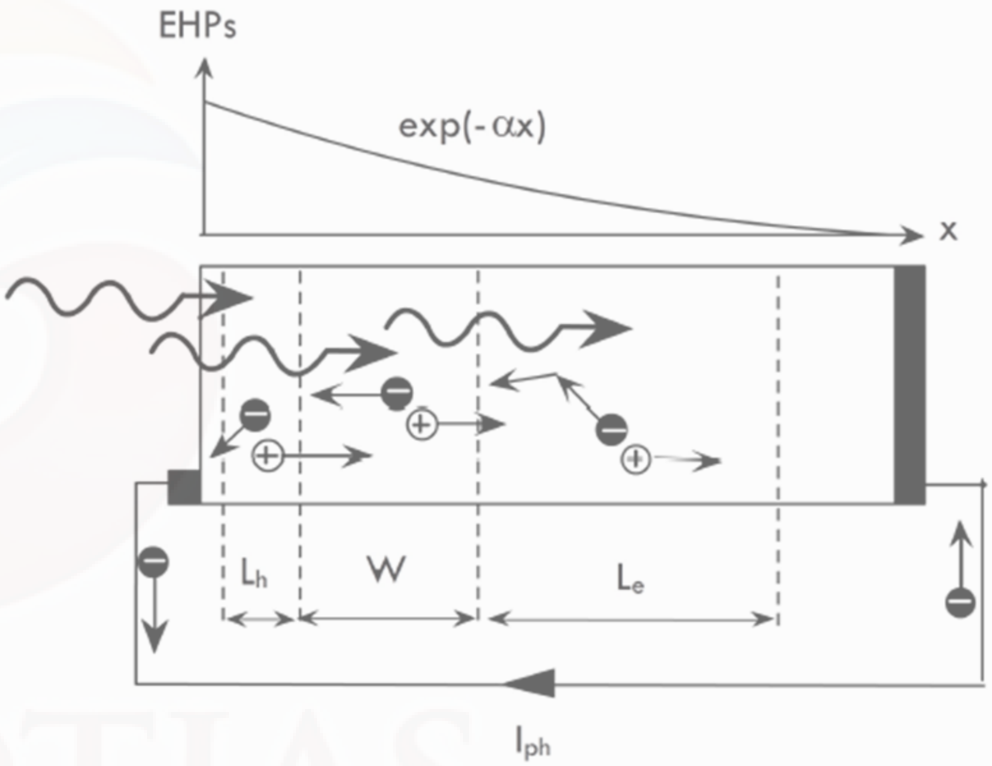


Figure : Photo generated carriers in a solar cell due to absorption of light. w is the width of the depletion region, while Lh and Le are minority carrier diffusion lengths in the n and p regions. The amount of absorption reduces with depth and hence the depletion region must be close to the surface to maximize absorption. This is achieved by having a thin n region. Adapted from Principles of Electronic Materials - S.O. Kasap

Solar cell I-V characteristics

It possible to calculate the I-V characteristics of the solar cell by considering its equivalent circuit. The I-V characteristics depend on the intensity of the incident radiation and also the operating point (external load) of the cell. Consider a pn junction solar cell under illumination, as shown in this figure. If the external circuit is a short circuit (external load resistance is zero) then the only current is due to the generated EHPs by the incident light. This is called the photocurrent, denoted by Iph. Another name for this is the short circuit current, Isc.

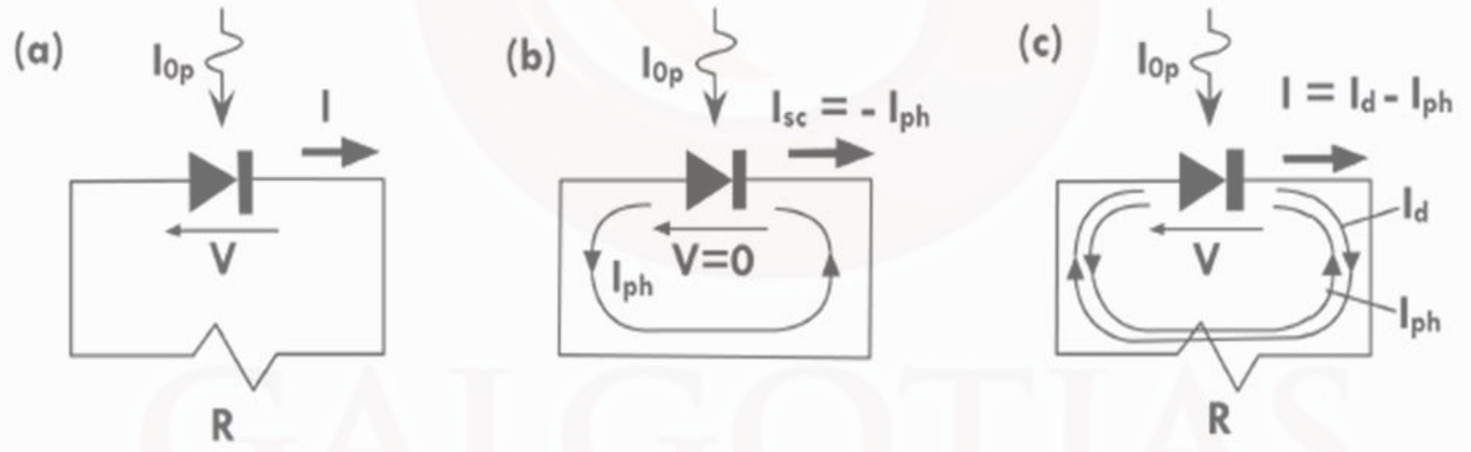


Figure (a) shows the pn junction solar cell under illumination with an external load. The equivalent circuit (b) without and (c) with an external load. The illumination causes a photocurrent to ow through the external circuit. When an external load is applied the potential drop across it creates a forward bias current, that opposes the photocurrent. Adapted from Principles of Electronic Materials - S.O. Kasap

Solar cell I-V characteristics

By definition of current, this is opposite to the photo current and is related to the intensity of the incident radiation, I_{op}, by

$$I_{sc} = -I_{ph} = -kI_{op} \tag{1}$$

where k is a constant and depends on the particular device. k is equivalent to an efficiency metric that measures the conversion of light into EHPs.

Consider the case when there is an external load R, as shown in figure above.

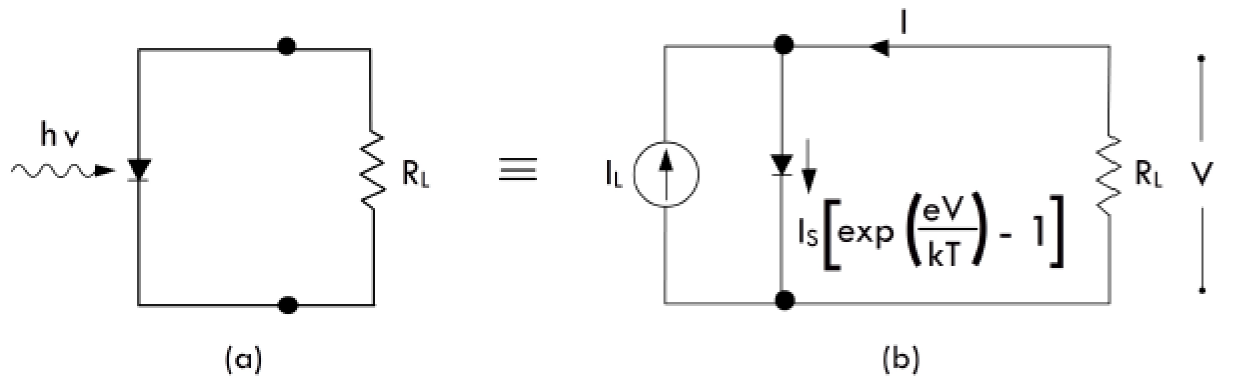


Figure : (a) A solar cell connected to an external load (b) Equivalent circuit, with a constant current source, a forward biased pn junction and the external load. The current from the forward biased pn junction opposes the constant current source. Adapted from Physics of semiconductor devices - S.M. Size.

Solar cell I-V characteristics

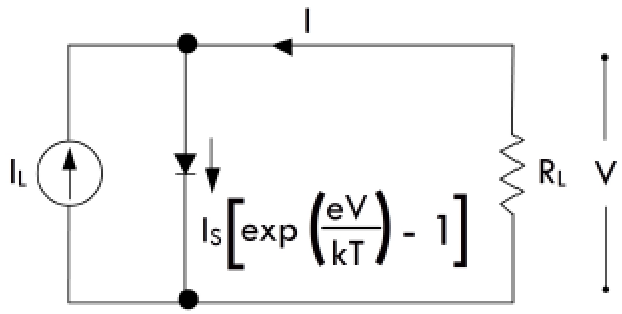
The equivalent circuit for this case is shown in figure above. There is a voltage across the external load, given by V = IR. This voltage opposes the built in potential and reduces the barrier for carrier injection across the junction. This is similar to a pn junction in forward bias, where the external bias causes injection of minority carriers and increased current. This forward bias current opposes the photo current generated within the device due to the solar radiation. This is because Iph is generated due to electrons going to the n side and holes to the p side due to the electric field within the device, i.e. drift current while the forward bias current is due to diffusion current caused by the injection of minority carriers. Thus, the net current can be written as

$$I = -I_{ph} + I_d$$

$$I_d = I_{s0}\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right] \qquad (2)$$

$$I = -I_{ph} + I_{s0}\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right]$$

Equations-- A



(b)

where Id is the forward bias current and can be written in terms of the reverse saturation current, I_{s0} and external voltage, V .

Solar cell I-V characteristics

The overall I-V characteristics is plotted in figure below

In the absence of light, the dark characteristics is similar to a pn junction I-V curve. The presence of light (Iph) has the effect of shifting the I-V curve down. From this figure , it is possible to define a photo current I_{ph}, which is the current when the external voltage is zero and an open circuit voltage, V_{oc}, which is the voltage when the net current in the circuit is zero. Using equation 2, Voc can be calculated as

$$I_{ph} = I_{s0}\left[\exp\left(\frac{eV_{oc}}{k_B T}\right) - 1\right]$$

$$V_{oc} \approx \frac{k_B T}{e} \ln\left[\frac{I_{ph}}{I_{s0}}\right] \qquad (3)$$

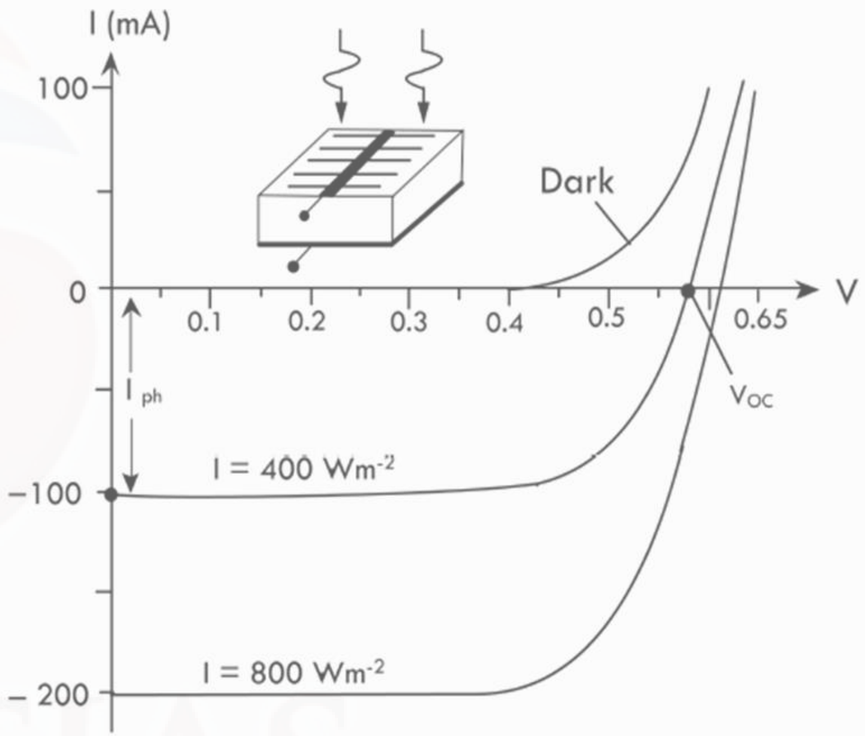


Figure: I V characteristics of Si pn junction solar cell under dark conditions and under illumination with light of increasing intensity. Short circuit current and open circuit voltage both increase with increasing illumination. Adapted from Principles of Electronic Materials - S.O. Kasap

Solar cell I-V characteristics

The overall *I–V* characteristics of a typical Si solar cell are shown in Figure. It can be seen that it corresponds to the normal dark characteristics being shifted down by the photocurrent I_{ph}, which depends on the light intensity *I*. The open circuit output voltage V_{oc}, of the solar cell is given by the point where the *I–V* curve cuts the *V* axis (*I* = 0). It is apparent that although it depends on the light intensity, its value typically lies in the range 0.5–0.7 V.

The area under the curve, corresponding to I_m and V_m, gives the maximum power. It can be seen that the maximum power is directly proportional to Voc and can be increased by decreasing I_{s0}.

$$P = IV = I_{s0}V\,[\exp(\frac{eV}{k_BT}) - 1] - I_{ph}V$$

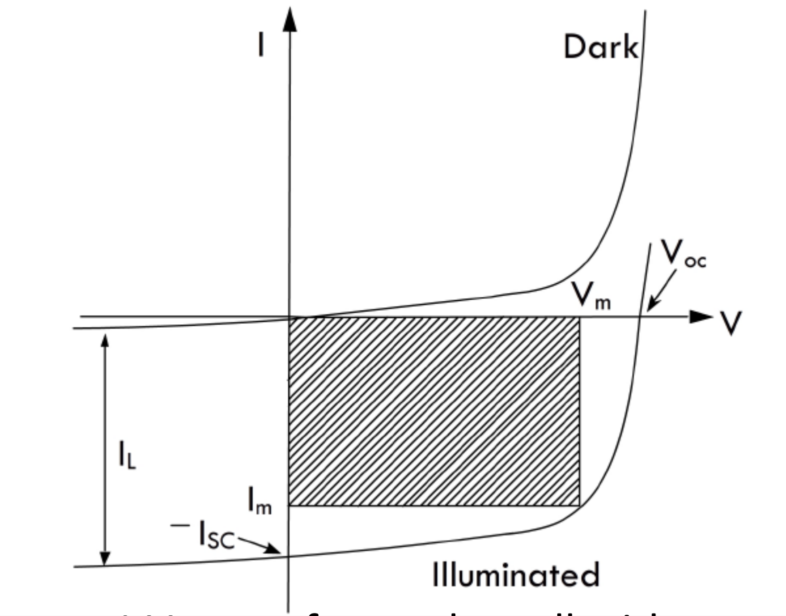
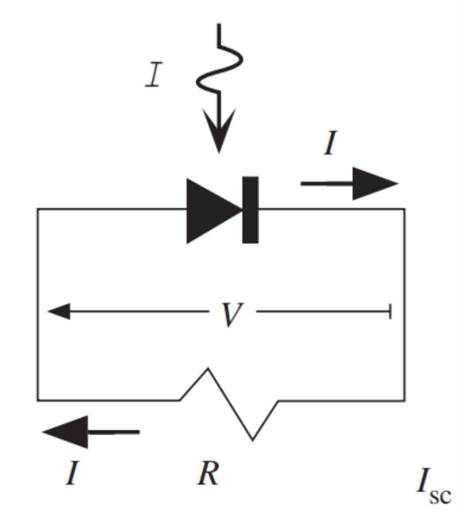


Figure : I-V curve for a solar cell with maximum power indicated by the shaded area. The corresponding voltage and current are Vm and Im. The value depends on the external load applied

Solar cell I-V characteristics

When the solar cell is connected to a load as in Figure, the load has the same voltage as the solar cell and carries the same current. But the current *I* through *R* is now in the opposite direction to the convention that current flows from high to low potential. Thus, as shown in Figure

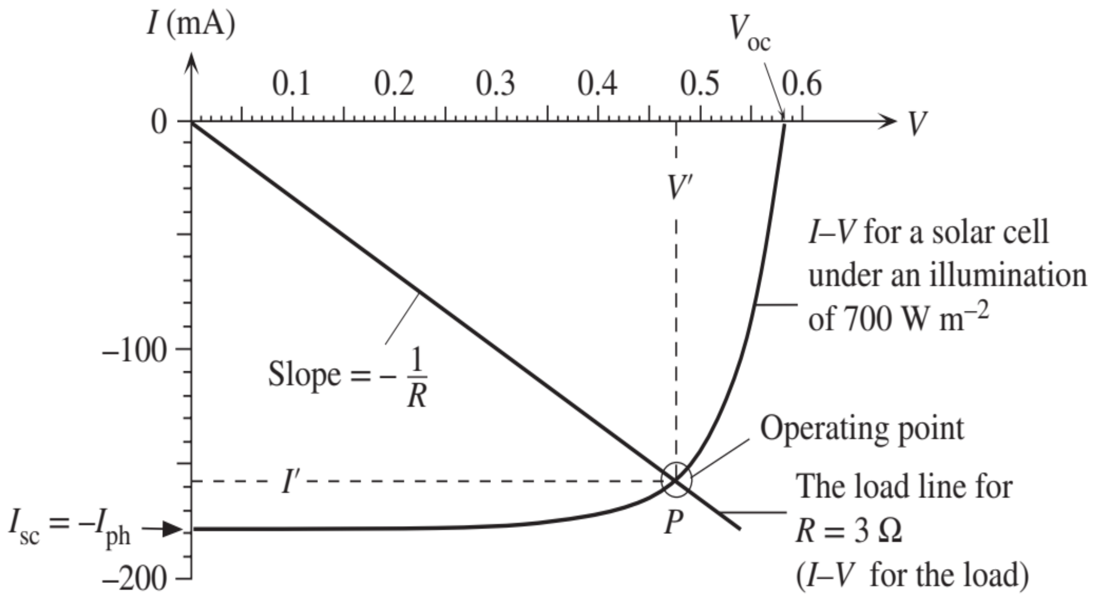
$$I = -\frac{V}{R}$$ Equations-- B



The actual current *I′* and voltage *V′* in the circuit must satisfy both the *I–V* characteristics of the solar cell, and that of the load. We can find *I′* and *V′* by using a graphical solution. *I′* and *V′* in the solar cell circuit are most easily found by using a **load line construction.** The *I–V* characteristics of the load in Equation B is a straight line with a negative slope -1/*R*. This is called the **load line** and is shown in Figure along with the *I–V* characteristics of the solar cell under a given intensity of illumination. The load line cuts the solar cell characteristic at *P* where the load and the solar cell have the same current and voltage *I′* and *V′*. Point *P* therefore satisfies both Equations A and B and thus represents the **operating point of the circuit.**

Solar cell I-V characteristics

The **power delivered** to the load is $P_{out} = I'V'$, which is the area of the rectangle bound by the I and V axes and the dashed lines shown in Figure



Maximum power is delivered to the load when this rectangular area is maximized (by changing R or the intensity of illumination), when $I' = I_m$ and $V' = V_m$. Since the maximum possible current is I_{sc} and the maximum possible voltage is V_{oc}, $I_{sc}V_{oc}$ represents the desirable goal in power delivery for a given solar cell.

Fill Factor and efficiency of solar cell

The product of open circuit voltage V_{OC} and short circuit current I_{SC} is known a ideal power.

Ideal Power $= V_{OC} \times I_{SC}$

The maximum useful power is the area of the largest rectangle that can be formed under the V-I curve. If V_m and I_m are the values of voltage and current under this condition, then

Maximum useful power $= V_m \times I_m$

The ratio of the maximum useful power to ideal power is called the fill factor

$$\therefore \quad \text{Fill factor} = \frac{V_m \times I_m}{V_{OC} \times I_{SC}}$$

$$\text{Efficiency of solar cell} = \frac{\text{Output power}}{\text{Input power}}$$

Questions:

- What do you mean Photovoltaics?
- Describe the solar cell working principle
- Explain the fill factor and efficiency of solar cell

References

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